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Optical Fiber Sensor System for electric field environments

Inventors:	Ignacio Valenzuela	Cable/Circuit
	Jon Scott	Switches
	Melissa Crenshaw	Cable Retractor/HOE method
	David Todd	Reflector method - VCSEL w NIR POF
	Somow	Circuit mods to initial design & software design
	Kent Keihl	grad student, original need
	John Kidder	Systems Integration

Summary of the Invention

The invention relates to an optical sensor system which overcomes inherent problems and limitations of known fiber optic sensor systems used in Radio Frequency (RF) environments including Magnetic Resonance Imaging(MRI). The preferred embodiment is specific to measuring patient response to audio and other stimuli while in the MRI unit, by using a fiber optic position sensor for switching response, and includes controller module, fiber optic cable and mechanical actuator subsystems. Specific benefits include: no effects from magnet, no ferrous materials, no signal artifacts. To one skilled in the art, the benefits of the invention, including ease of use and economical manufacturing, may apply to a variety of fiber optic sensor systems suitable for MRI use. One object of the invention is to provide a non-ferrous sensor and cable lead that may extend from the interior of the MRI unit to a controller module external to the MRI room. Long fiber optic leads are generally required, for detection and transmission of the sensor light signal. The invention achieves repeatable and stable detection of the modulated light signal and overcomes typical limitations of signal losses in fiber-coupling and absorption by the fiber material, and can be used at a range of fiber optic lengths including the typical requirement of 35 feet. The sensor and cable lead sub-systems could include all-plastic components, to provide a flexible, rugged and lightweight cable using for example, plastic optical fiber, however non-ferrous materials that are not plastic may also

be used. Another object is to have a flexible and rugged fiber optic cable system that can survive operational handling and frequent storage, typical of frequent changes of the MRI setup and patients, and also rapid movement of heavy medical equipment in the vicinity of the optical sensor. A final object of the invention is to be economical to manufacture and provide substantial durability typical of a reusable medical device. The preferred embodiment is described as an optical fiber sensor that detects switching by the patient in the MRI and outputs an electrical response at an external controller location a significant distance from the MRI unit.

The invention includes the following sub-systems: a controller module, a fiber optic cable and an actuator/sensor. The controller module may include at least one light source, at least one detector, a fiber optic interface, an electronic processing circuit, a power supply and an electrical switch output. The fiber optic cable system may include at least one optical fiber, at least one cable jacket system, and appropriate mechanical interconnects. The actuator/sensor may include at least one interface to the fiber optic cable system, mechanical actuators, optical components to modulate the transmitted light by modifying optical characteristics in the path between transmitting and receiving optical fibers, the optical components being typically mechanically actuated to modulate the analog optical signal. The preferred embodiment provides 4 hand activated fiber switches and includes a cable subsystem with 4 transmission fibers and 4 receiving fibers which are permanently fixed, one end at a switch box accessible to the patients hand, and the other end at the controller module which also supplies 4 independent electrical switching signals corresponding to the mechanical actuator switching. Each mechanical actuator is mounted in the switch box and controls the position of an optical filter interposed

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between each transmitting and receiving fiber. The present invention is not limited to the number of switches or fibers of the preferred embodiment and it is obvious to one skilled in the art that multiple switch embodiments can be made with multiple optical fibers.

There are many alternate embodiments, including the use of all plastic interconnects for the optical fiber termination to easily detach the cable at various locations for storage or repair. The interconnects may be located at the controller module, the patient switch box or just external to the MRI unit. A further embodiment of the detachable flexible cable may include the use of a retractor for ease of compact storage without damage to the fiber transmission, which would be typical in optical sensors using glass optical fibers.

There are several other embodiments for the switching modulation of the light signal at the actuator. For example a more compact switching enclosure is possible using a reflector type actuator with a bundled fiber array incorporating transmission and receiving fibers. Other embodiments can be made using single optical fibres with reflective modulators. For use with mechanical actuation not necessarily perpendicular to the fiber optic, a holographic optical element such as a grating, can be translated mechanically to spatially separate a white light transmitted signal into an array of fibers corresponding to different wavelengths. The optical fiber system embodiments include extension to multiple actuators for a keypad controller, obvious to one skilled in the art. Further embodiments using specific material sub-components will be detailed in the description for further embodiments of the invention.

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Detailed Description of the Preferred Embodiments

Optical fiber sensors can incur substantial signal loss dependent on the length, material and core size of the optical fiber, coupling to the light sources, which may limit the length of optical fiber that still allows reliable sensor operation. The present invention allows a substantial length of optical fiber between the controller and patient module. Further, glass optical fiber systems are less suitable for frequent operation in a medical environment such as the MRI due to fragility, difficult storage due to thick and inflexible cables, and standard glass optical fiber connectors typically contain metallic material. The present invention permits frequent and flexible handling of the optical fiber cable system, fast and compact storage and non-ferrous materials. The present invention also allows fast and repeatable response to the patient motion. This is suitable for measuring patient response to a wide range of stimuli while directly monitoring all or some of the scan information.

The preferred embodiment is an optical fiber sensor that detects switching activated by the patient inside the MRI and outputs an electrical response at an external controller location a significant distance from the MRI unit.

Referring to Figure 1, the preferred embodiment of the optical fiber sensor system 10 is illustrated. The system 10 is shown in use with a patient 12, disposed in an electric field 13 such as the RF field associated with a MRI system 20. The optical fiber sensor system 10 includes at least one of the following sub-systems: a controller module subsystem 14, a fiber optic cable subsystem 16 and an actuator/sensor subsystem 18.

The controller subsystem is further detailed in Figure 2 to demonstrate the principles of operation for the preferred embodiment, and may include light sources, detectors, processing and peripheral interfaces. The operation of the controller is to detect the modulation of the light signal at the actuator and convert this light modulation to an electrical switching signal. Light sources 22 are Light Emitting Diodes (LEDs) with operating wavelength at 660nm , and can be bonded with adhesive to the emitter optical fibers 24 with low optical loss. The LED wavelength is selected to match a minima of absorption loss in the optical fiber, however the invention is not limited to this wavelength, emitter or fiber type as there are other emitter-fiber combinations that provide identical function. As will be shown in later embodiments, the light source is not restricted to LEDs and white light lamp sources or laser diodes can also be used, however the LED is optimal in this embodiment for economical, reliable and compact operation. There are 4 light sources in the preferred embodiment, each of which is bonded with adhesive to a plastic optical fiber of 0.5mm diameter, and typically made from polymethylmethacrylate (PMMA). There are photodiodes 28 for light detection, with methods provided for mechanical interconnections with the detector optical fibers 24. A Load resistor is connected to each detector output for the purpose of clipping the output signal to improve the rise time.

The processor circuit 33 is a standard design as shown in Figure 3 and is obvious to one skilled in the art. The analog signal is output to an inverting comparator. The comparator generates a digital low signal that precisely tracks the change in the optical signal, and the intrinsic fall time of the comparator signal is on the order of several microseconds. The

comparator output is buffered by an RS-232 line driver. Total electronic delay time from sensing the optical switching to output of an electrical signal from the RS232 driver is 5 us, suitable for a wide range of patient response detection. Peripheral components of the controller subsystem are also shown in Figure 2: a AC/DC adapter 40, voltage regulator (not shown) indicator LED 44, controller enclosure 46. The benefits of the controller subsystem are repeatable and sensitive detection of modulated analog light signals by utilizing efficient coupling to the optical fiber and electronic processing of the detected signal, and fast switching response of patient activation of sensor actuator.

The fiber cable sub-system provides delivery of the light signals to and from the mechanical actuator system, and is shown in Fig. 4. The fiber optic cable system 16 includes at least one optical fiber 24 and at least one outer jacket 34. In the preferred embodiment, there are 8 optical fibers. The fibers may be bare inside the outer jacket, or each may commonly have its own protective tubing jacket(not shown). For the advantages of storage and repair, the cable may be detachable at the controller module, the mechanical actuator system or at an appropriate location along the cable path that is accessible. The detachable cable embodiment necessitates fiber optic interconnects (not shown), which are designed to be rugged and easy for non-trained personnel to connect and store. As shown in Fig.4, the cable of the preferred embodiment is split at the end nearest the MRI to create dual mechanical actuator systems for operation by left and right hands. Another embodiment is a cable that is contiguous for only 1 mechanical actuator system. It is also obvious to one skilled in the art, that the two switch boxes could be located in series along the optical fiber cable, however, for cable management inside the restricted MRI interior, the split cable is the preferred embodiment. A key functionality

of the cable system is rapid storage, due to reconfiguration of the MRI system and surrounding equipment. A cable retractor 38 achieves rapid storage of the cable when it is disconnected, by coiling it under tension in a housing that may be hung on a clip or easily stored. The cable retractor has a release to permit easy unwinding of the cable. The unique mechanical properties of the optical fiber cable system when used with plastic optical fiber, allow this compact storage, by providing flexibility for coiling, and ability to withstand compression of the outer jacket without damaging the optical fiber 24. Hence the optical fiber cable system provides optimal light signal delivery in a medical environment, compact storage and ease of connection.

The mechanical actuator system 18 is proximal to the patient's hands inside the MRI, and actuation of the switch by the patient modulates the optical characteristics of the light signal traveling from the emitter to the corresponding detector fiber as shown in Fig. 5a. A variety of actuator designs will work as a switch, including sliders, rockers, toggles and pushbuttons. Fast patient response is a necessity for certain patient testing within the MRI, and hence the mechanical system is required to be sensitive to the patient motion while still retaining the required optical tolerances to smoothly vary the optical signal in free space external to the optical fibers. The preferred embodiment is a push button actuator 74 on top of a elastomer spring 42. In the preferred embodiment, the push button is solidly mounted to a plastic retaining block 36 which is mounted in the switch box 32, and as shown, the lower rod part of the push button is attached to the optical filter 48 that is moved in and out of the optical path A-A between emitter and detector fibers. The optical fibers 24 from the optical cable system are connected to the retaining block 36 as follows; The fibers are terminated in plastic ferrules 44 which have a fin for registration

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against the edge of the block. The ferrules are then inserted in opposing side holes in the retaining block such that the centers of both emitter and detector fibers are co-linear with the optical path. The ferrules are inserted to a predetermined position leaving a small gap between the two ferrule surfaces to permit the optical element to move across the optical path. In the preferred embodiment the dimensional tolerances of the ferrules and holes in the retaining block are suitable for fiber optic connection with minimal misalignment losses. Further, the mounting and processing of the plastic fiber ends are standard methods common in the art. The attachment of the optical filter is by use of an adhesive (not shown) and as the preferred optical element is a plastic optical filter 48, there is reduced mechanical wear between the moving parts and the ferrule face, during repeated use. The preferred optical filter is a blue colored polymer filter film, used to absorb the red optical signal when moved in the optical path A-A. The preferred embodiment of the mechanical actuator system is shown in Fig 5b, demonstrating 2 switches each, in two separate enclosures for use with the patient's left and right hands. The preferred embodiment of the mechanical actuator system provides a fast switching response time, such that the electronic switching time is less than 1 millisecond, which is optimum for many patient response measurements.

There are alternate embodiments of the optical fiber system, that incorporate different methods of analog optical switching. These include a reflector type optical fiber switch and a spectral grating type optical fiber switch, and the subsystems of both differ from the preferred embodiment. Typically, these methods have increased optical loss at the switching region in comparison to the preferred embodiment, however, they provide similar benefits of fast switching and rugged mechanical operation.

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A reflector type embodiment of the optical fiber system is shown in Fig.6. The optical fiber cable includes at least one emitter fiber 50 and at least one detector fiber 52. As is common in the art, for decreased coupling loss due to the large numerical aperture typical of the plastic optical fiber, an array of smaller detector fibers may be mounted and terminated in a ferrule or holder 56, so as to surround at least one larger emitter fiber. A reflector 54 is mounted on a push button switch as per the preferred embodiment of the mechanical actuator system, such that actuating the push button moves the reflector in front of the fiber surfaces. The reflector material may be a plastic or a thin coating of semiconductor or metal. In the off state of the switch, there is a nominal electrical signal corresponding to the Fresnel reflection from at least one fiber end, and in the on state, the light signal is large as the emitter fiber light is reflected back into the detector fibers with minimal loss. The electronic control module is similar in operation to the preferred embodiment, and provides an electrical output when the detected signal from the photodiode increases from a predetermined low voltage to a predetermined higher voltage.

An embodiment using a spectral grating type optical fiber switch is shown in Fig 7. The principle of operation is to send a broadband wavelength signal such as white light, to the switching region, and modulate the broadband wavelength signal into discrete wavelength bands by use of a non-metallic grating, such that the ratio of light in an array of detector fibers is modulated with grating position. The emitter in the controller module is a white light source (not shown), such as a filament lamp with reflector common in the optical fiber art. The light source is coupled to at least one emitter fiber 24, which extends

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through the optical fiber cable system to the mechanical actuator system. In place of the absorption filter used in the preferred embodiment, an optical grating 62 is positioned such as to diffract the light into discrete wavelength regions as a function of angle from the grating. The preferred grating is a holographic optical element as it is all plastic and economical. The mechanical actuator system differs from the preferred embodiment in that the actuator 64 may be of rotary or slider (not shown) form to adjust the grating over an appropriate range relative to the emitter and detector fibers, such that the difference in signals detected in each fiber in a detector array 66 provides suitable electronic sensitivity for fast and repeatable switching . The retaining block is made large to accommodate the linear fiber array 66, as shown in Fig. 7, this array may be in the form of a ribbon of plastic optical fibre. This embodiment is particularly suited to extension to a variable switching optical sensor system.

A final embodiment is shown in Fig.8 , the preferred embodiment with long cable lengths above the typical 35 feet required for most MRI patient monitoring systems. A high power laser emitter 70 in the near infrared and a plastic optical fiber 72 with low absorption in the near infrared region are used to overcome existing limitations due to overall signal efficiency. Recently, new laser emitter devices, suited for low current drive, efficient and simple coupling to large core optical fiber, are commercially available. In particular, the vertical cavity surface emitting laser (VCSEL) is distinct from other laser diode sources in that it provides a large collimated output beam with low divergence which is ideal for high efficiency coupling to a large core plastic optical fiber. A VCSEL laser with operating wavelength near 660nm could be used with the PMMA optical fiber, to maximize overall signal transmission through the optical fiber sensor

system. As laser diodes are typically more efficient at near infrared wavelengths due to the semiconductor characteristics, an embodiment for increased cable length with similar switching sensitivity, includes a VCSEL at near infrared operating wavelength, typically around 800nm wavelength, combined with a polymer based optical fiber with low absorption in the same wavelength region. This unique combination would provide large input light power at reduced drive current, and also longer optical fiber lengths are possible due to reduced absorption by the optical fiber material, and the rugged and flexible benefits of a polymer optical fiber system are retained. Alternate embodiments include the use of other types of laser diodes, with the plastic optical fibre 72.

To one skilled in the art, it is obvious there are other known methods of changing the optical characteristics in the optical fiber sensor system. These other known switching methods, when combined with the described sub-systems to produce the invention, are included in the scope of this application.

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To one skilled in the art, it is obvious there are other known methods of changing the optical characteristics in the optical fiber sensor system. These other known switching methods, when combined with the described sub-systems to produce the invention, are included in the scope of this application.

Claims

We Claim:

1. A hand actuated control panel system that is compatible for use in electromagnetic fields such as generated in a magnetic resonance imaging system, containing a switch control comprising:

    a) A push button key made of non-ferrous material that neither conducts or emits electromagnetic energy when interacting with the fields created or measured during magnetic resonance imaging and mounted on

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b) a base designed to receive said key and made of a material with similar electromagnetic properties as ascribed to said key (a) and with

c) an elastomeric spring mechanism made of a material with similar electromagnetic properties to said key and disposed between the key and the base to return the key to its rest position once actuated and released and

d) an optical shutter connected to said key and made of a material with similar electromagnetic properties to key (a), that can be movably actuated to interrupt the optical path of a collimated or non-collimated light beam emitted from one optical fiber and collected by another optical fiber mounted in an optical block placed below said key and all said fibers and optical block components and fasteners made of a material with similar electromagnetic properties to key (a) and

e) a light source connected to the distal end of one of said optical fibers and placed outside of the range of significant interaction with the magnetic resonance imaging electromagnetic field and

f) a detector placed at the distal end of the other said optical fiber and placed outside of the range of significant interaction with the magnetic resonance imaging electromagnetic field and that transduces the optical signal to an electrical signal and

g) electronic circuitry that measures the change in the detector signal and provides an output signal that indicates that a key has been pressed

2. The hand control panel system of claim 1 that includes from 1-5 of said switch assemblies that can be actuated by one or more digits of one hand.

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3. The hand control panel system of claim 2 that includes two of said hand control panels, one for the left hand and one for the right hand of a two handed subject.

4. The hand control panel system of claims 1-3 where:

   a) the light emitting fiber and the light collecting adjacent to one another and

   b) the movable shutter is replaced by a movable reflector that returnably directs the light emitted from said emission fiber so that it is collected back into said collection fiber

5. The hand control panel system of claims 1-3 where:

   a) the light emitting fiber and the light collecting fiber are the same optical fiber and

   b) the movable shutter is replaced by a movable reflector that returnably directs the light emitted from said fiber so that it is collected back into said fiber

6. The hand control panel system of claims 1-5 where the light emitting fiber and the light collecting fiber are respectively replaced by a multiple optical fibers arranged side by side in a bundle.

7. The hand control panel system of claim 6 where the fiber bundle is constructed so that the fibers are fixed at the distal and proximal ends to relay coherent image of the light striking the surface of the bundle.

8. The hand control panel system of claims 1-3 where the shutter is a visible or near infrared wavelength region selective optical filter transmitting a selected wavelength band from about 10nm to about 150nm wide.

9. The hand control panel system of claims 1-3 where the shutter is a green transmitting optical filter.

10. The hand control panel system of claims 1-7 where the shutter is replaced by a an optical element such as a diffraction grating or prism which is movably disposed to transmit a specific wavelength between the emitting and collecting fiber.

11. The hand control system of claims 1-10 where the light source is a light emitting diode.

12. The hand control system of claims 1-10 where the light source is a laser diode.

13. The hand control system of claims 1-10 where the light source is a red light emitting diode.

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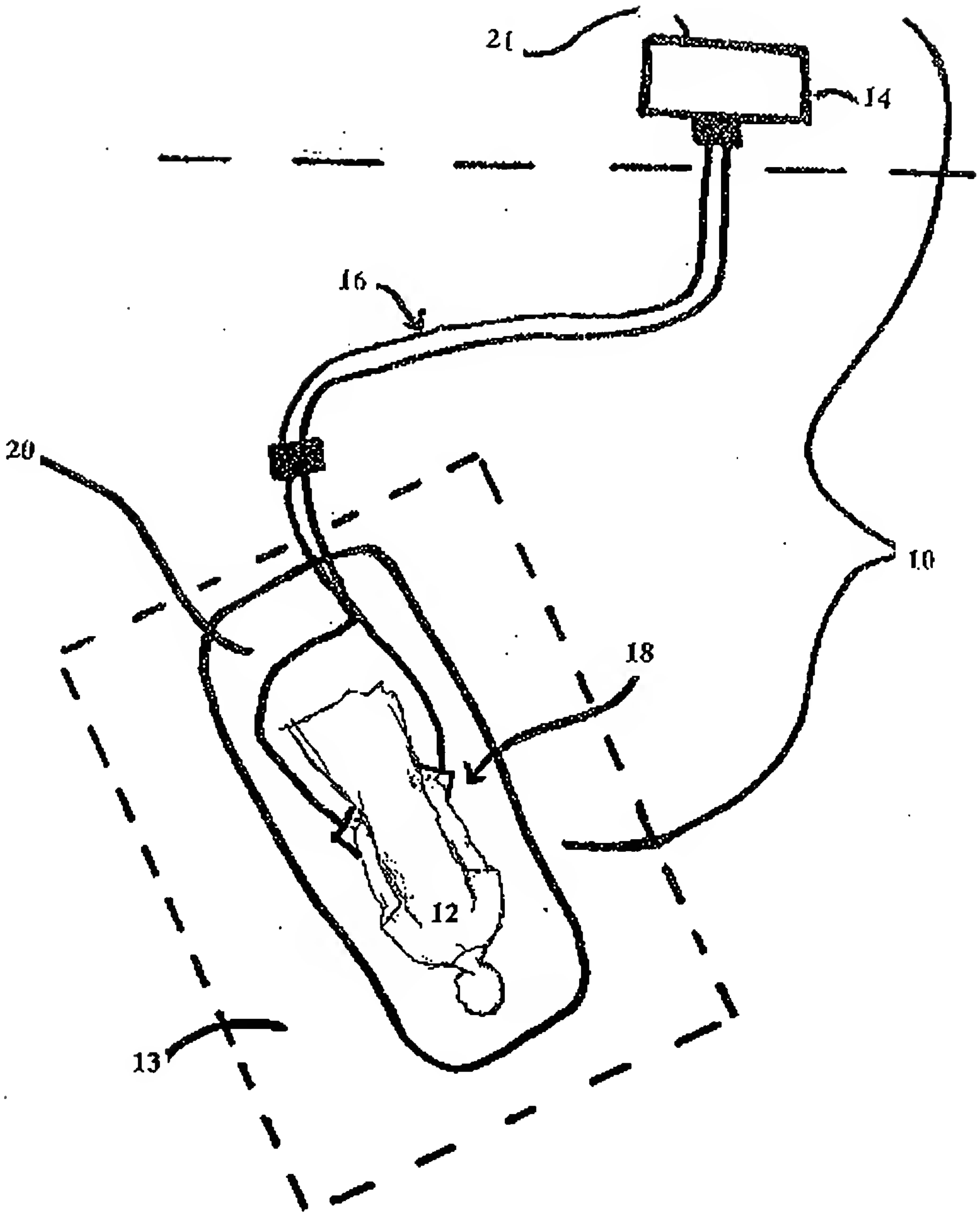

Fig. 1 Preferred embodiment of optical fiber system showing use in MRI for patient control

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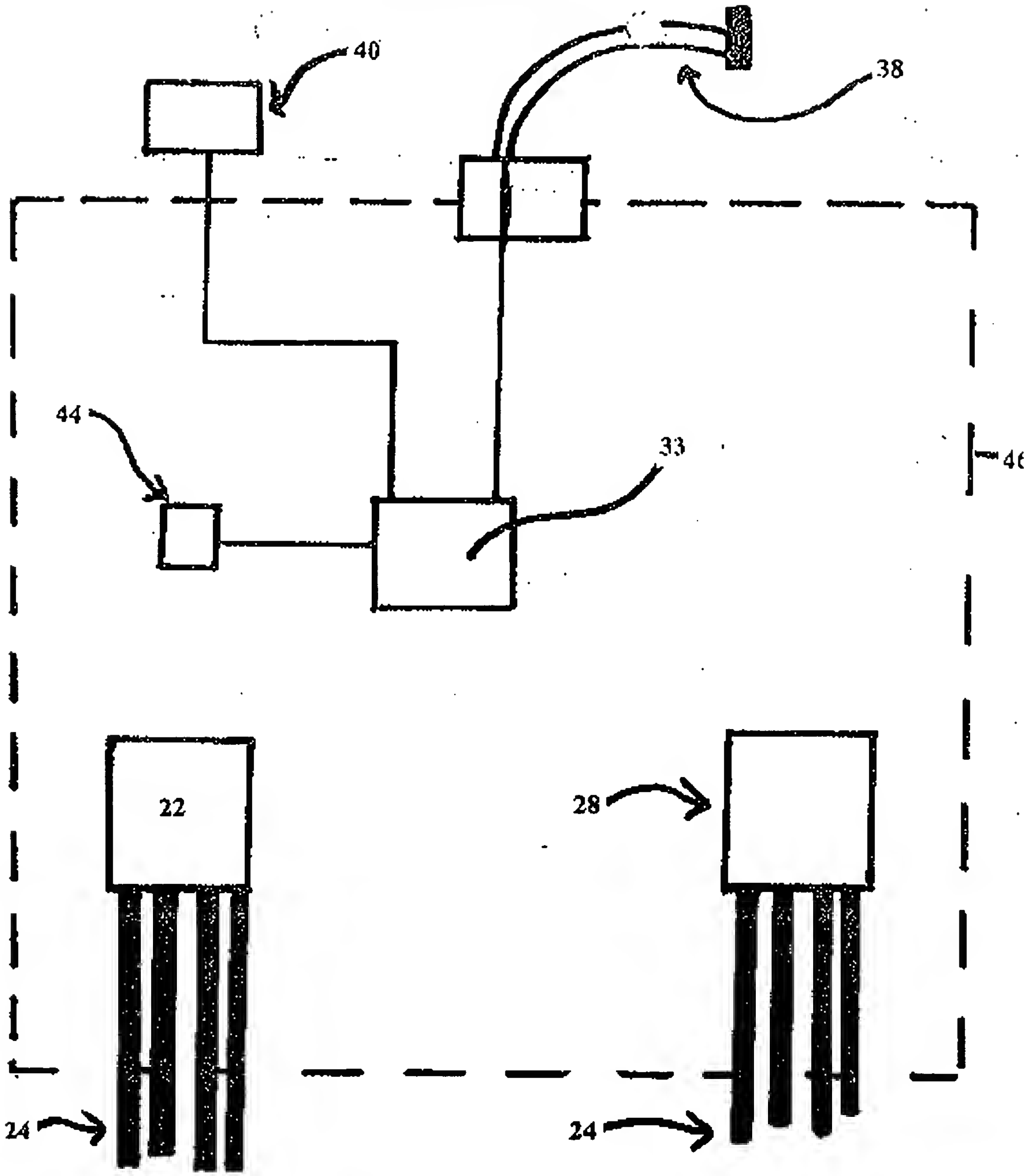

Fig. 2 Controller Module Sub-system

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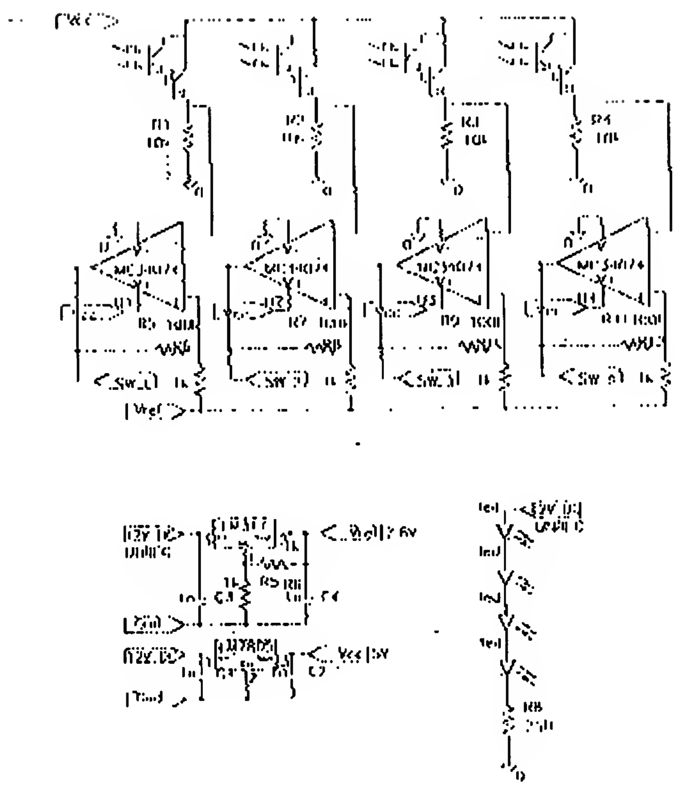

Fig. 3 Processing Circuit of Controller Module for preferred embodiment.

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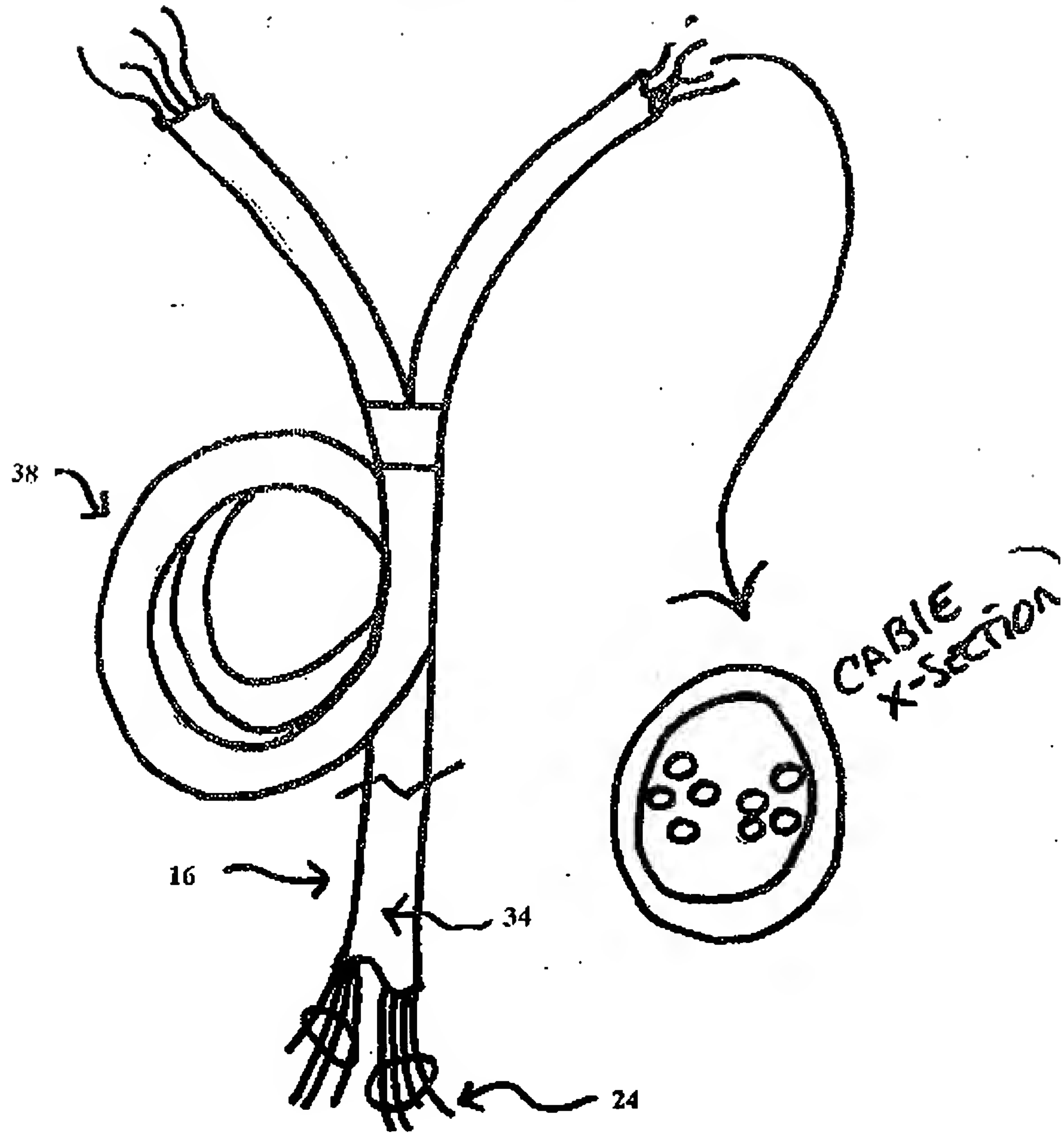
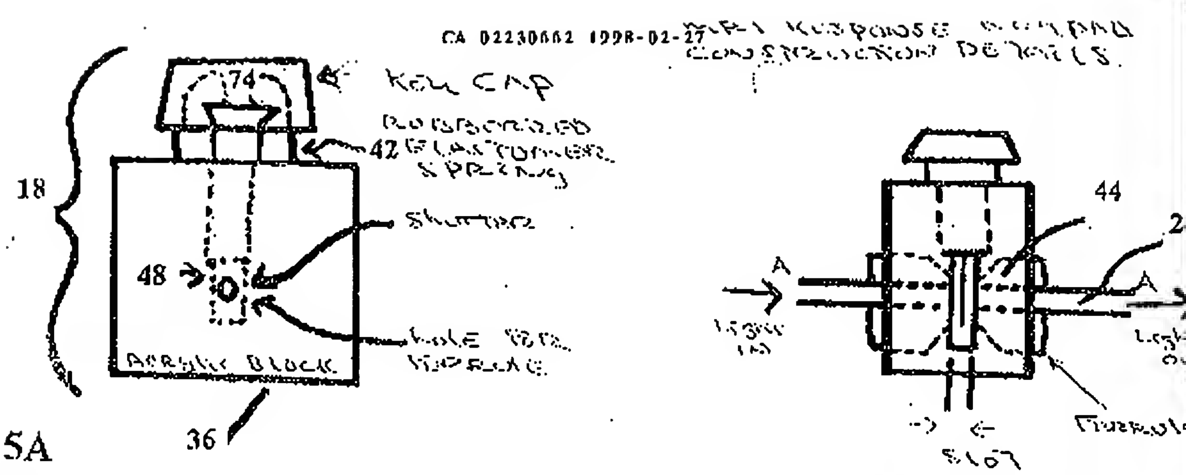


Fig. 4 Cable Subsystem showing optical fibers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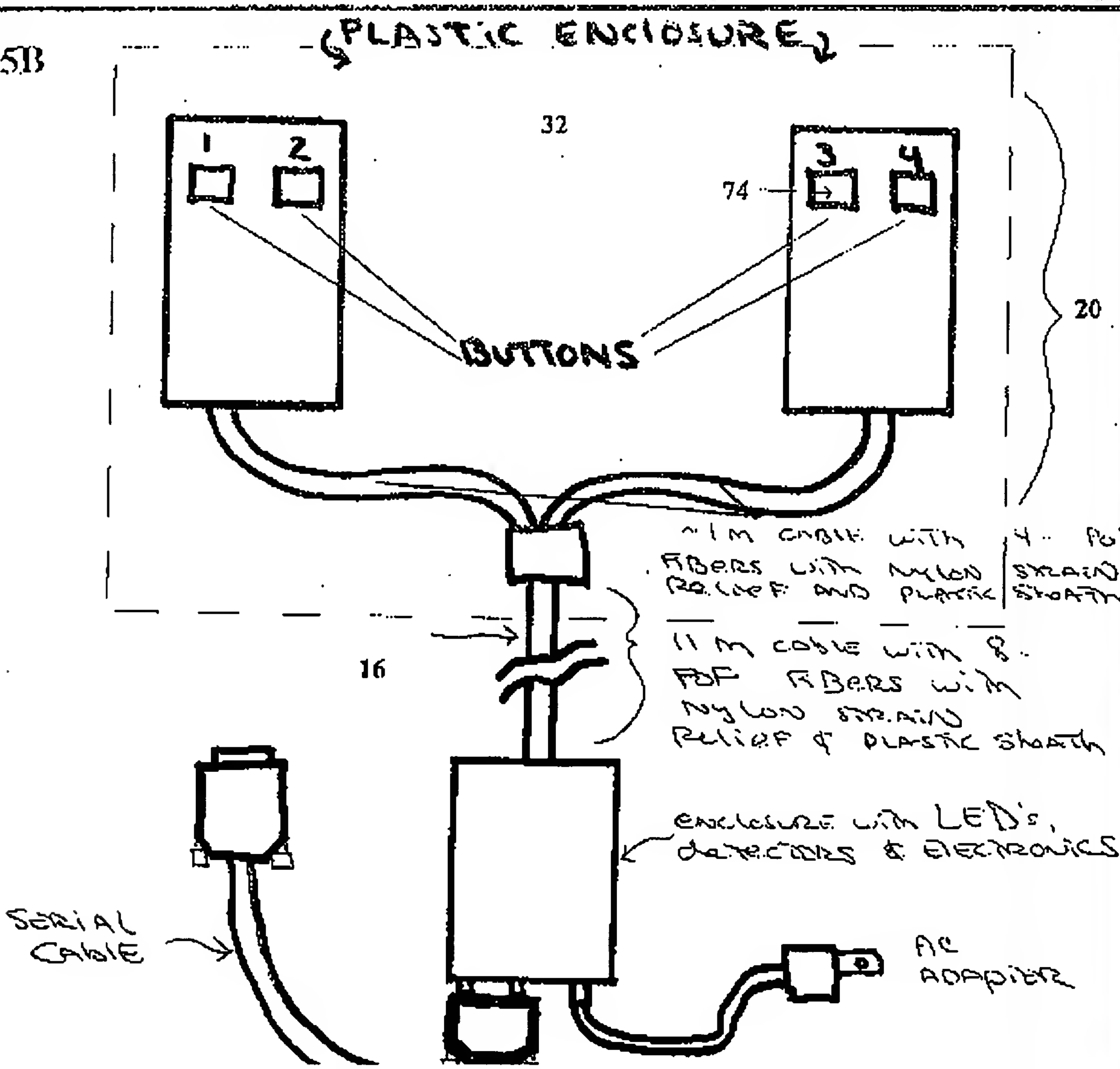
KEY CAP
74
42
RUBBERIZED ELASTOMER SPRING
18
SHUTTER
48
HOLE FOR LIGHT
ACRYLIC BLOCK
36
44
A
LIGHT IN
LIGHT OUT
SLOT

5A

5B


PLASTIC ENCLOSURE
32
1
2
3
4
74
BUTTONS
20
16
SERIAL CABLE
ENCLOSURE WITH LED's, DETECTORS & ELECTRONICS
AC ADAPTER

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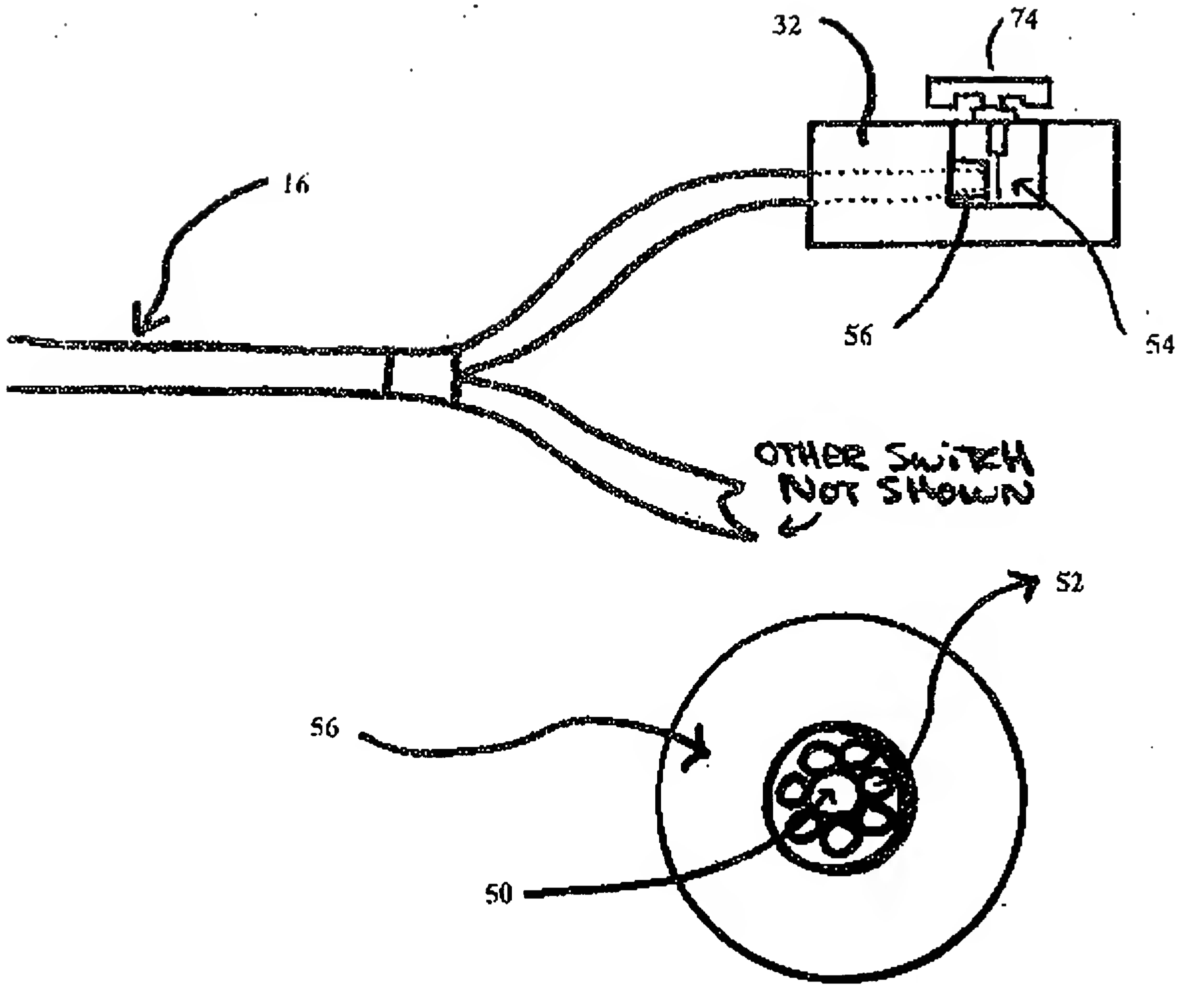

Fig. 6 Optical Fiber sensor system using reflector type switch including cross-section of optical fiber at the ferrule

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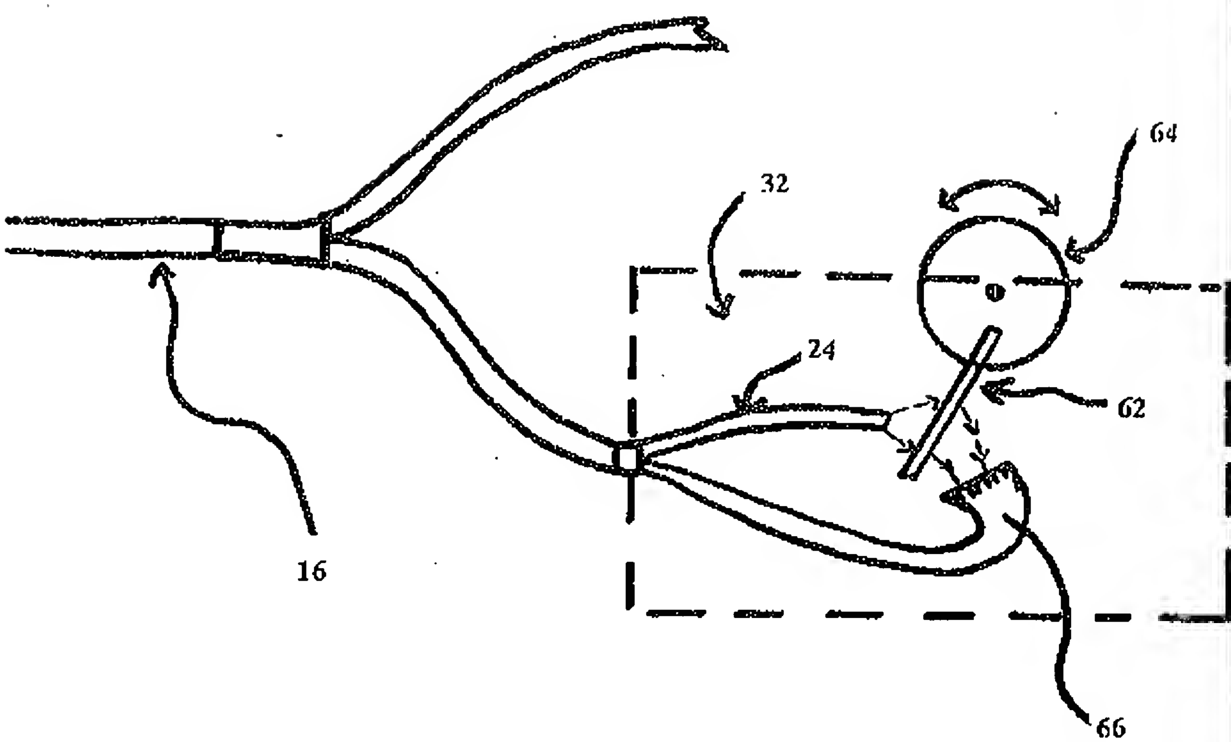

Fig. 7 Optical Fiber sensor system including holographic optical element for switching

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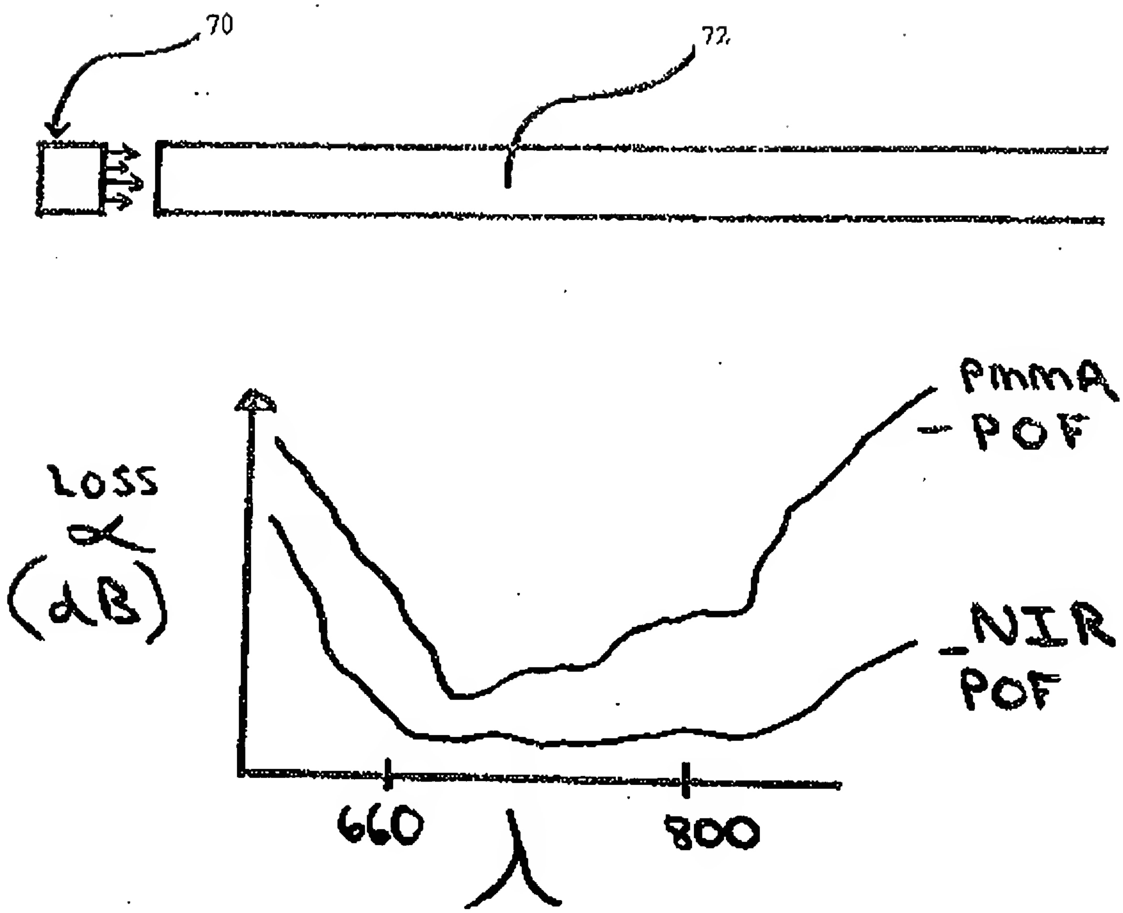

Fig.8 Optical Fiber Delivery included in an embodiment the fiber sensor system, with laser and optical fiber.

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Abstract

In electromagnetic fields, such as are found in magnetic resonance imaging devices, the metal conductors and components used in most switches cannot be used because of their interaction with the field. In functional magnetic resonance imaging where the subject is expected to respond to, or initiate certain actions, that would commonly be recorded or initiated by activating a hand-switch or keypad, there has gone unmet a need for a low-cost switching device without conductive metal parts to perform these functions. A non-ferrous fiber optic switch is proposed to perform this function